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Inventor(s): KNUDSEN DONALD CHRISTIAN ;
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ABSTRACT:

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(71) Applicant

Donald Christian Knudsen
R R #3, Perth, Ontario, Canada, K7H 3C5

(72) Inventor

Donald Christian Knudsen

(74) Agent and/or Address for Service

T Z Gold & Company
9 Staple Inn, London, WC1V 7QH

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Selected US specifications from IPC sub-classes
G01S H01Q

(54) Digital delay generator for sonar and radar beam formers

(57) Apparatus and a method of controlling the amount of delay or phase-shift which is applied to a signal received at or transmitted from each transducer in a multi-transducer antenna to produce a beam directed at a specific target point, includes, for each transducer, a first look-up table 7 for storing first digital words representative of the included angle between the lines joining the target to a reference point, and the same reference point to a transducer. A second look-up table 8 is associated with the first look-up table for each transducer, and stores second digital words representing delay or phase-shift control signals corresponding to ranges of the target relative to the reference point for each of said first digital words. Each first look-up table 7 is addressed with an address signal representing the direction of the line from the reference point to the target, to obtain a corresponding first digital word. Each second look-up table 8 is addressed with a corresponding first digital word combined with a signal representing the range of the target to obtain a corresponding second digital word. A signal received or transmitted by the corresponding transducer is delayed or phase-shifted an amount represented by the second digital word.

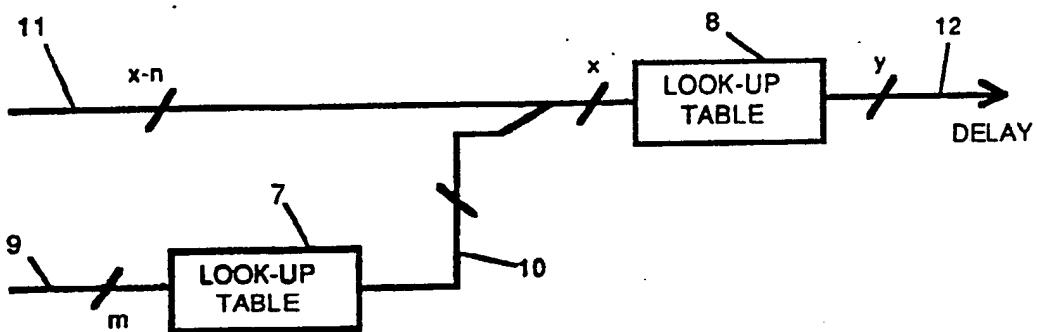


Fig. 2

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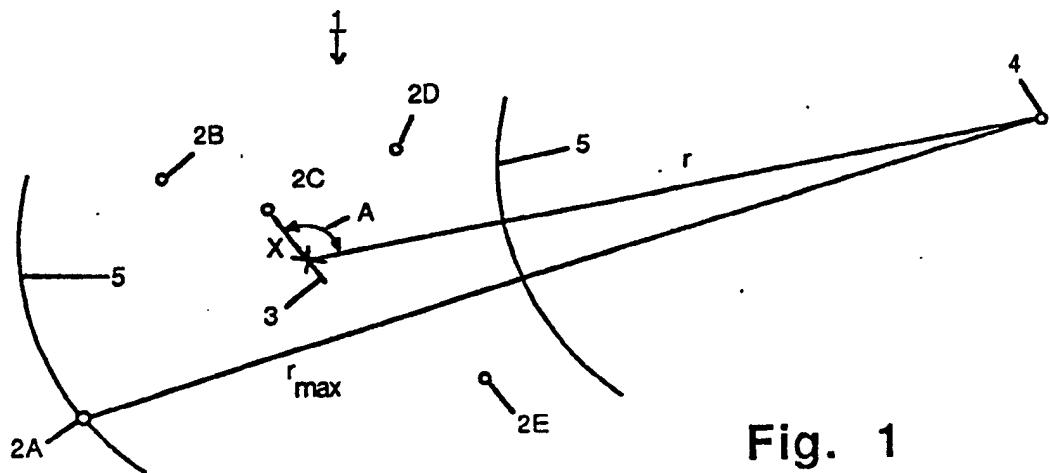


Fig. 1

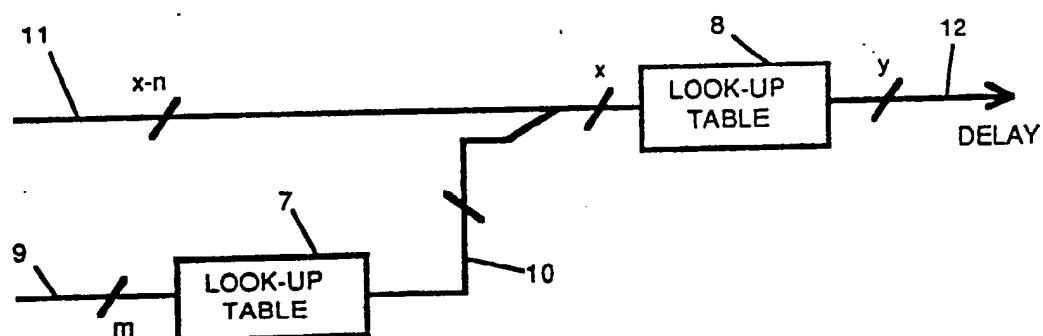
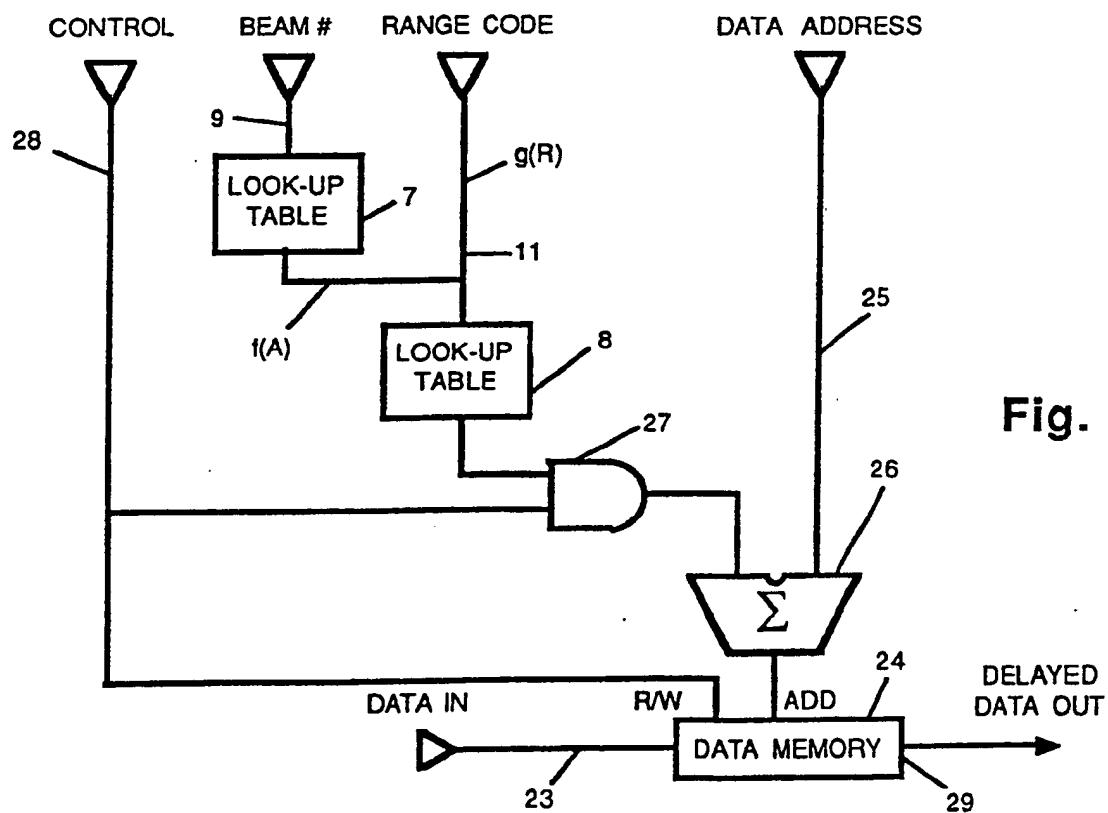
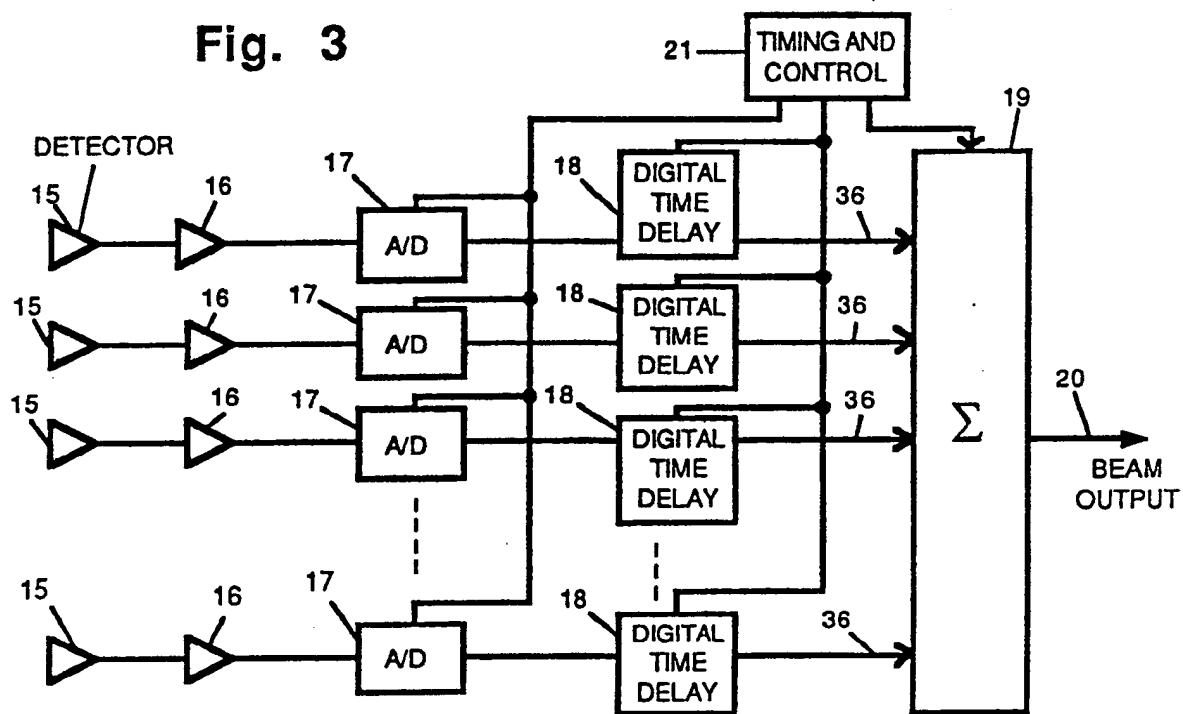


Fig. 2

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Fig. 3



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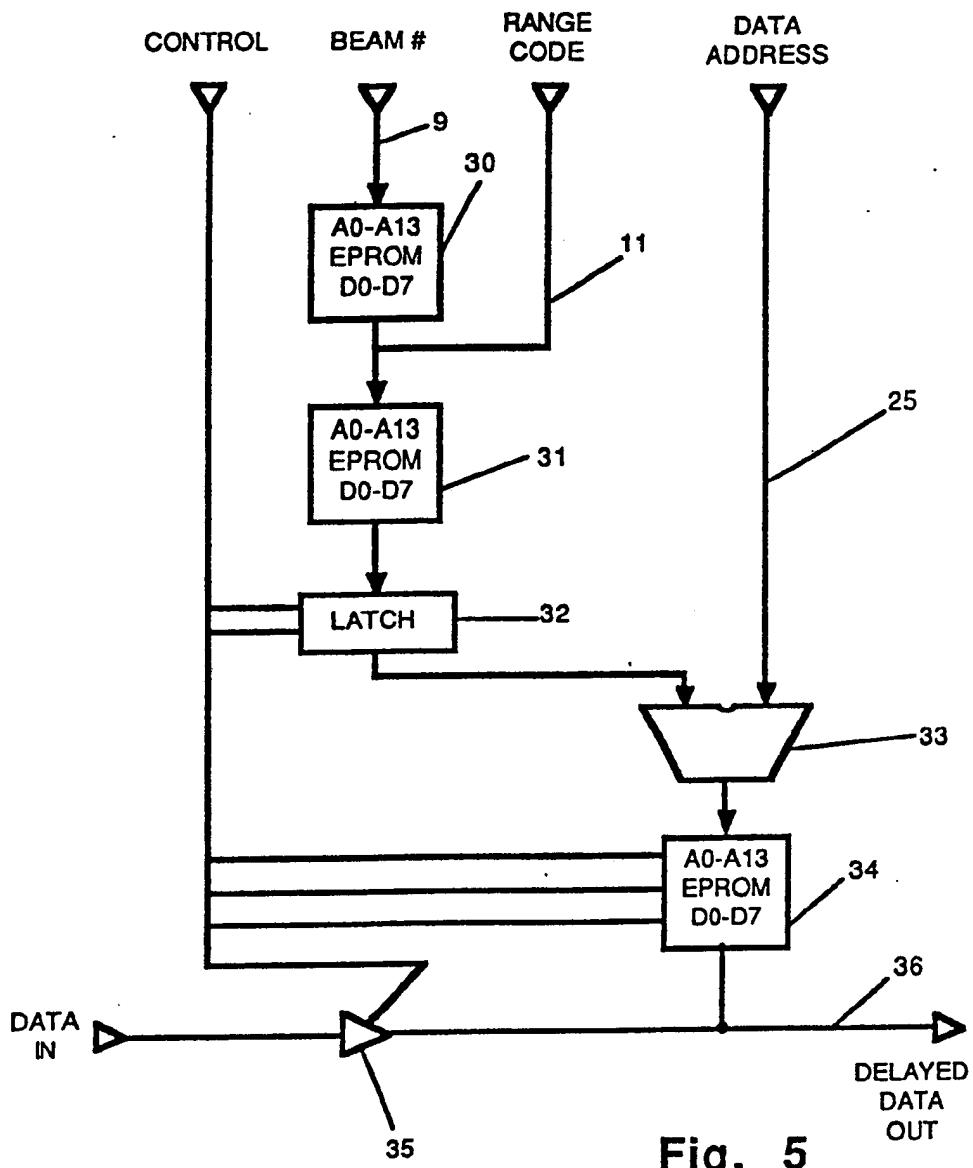


Fig. 5

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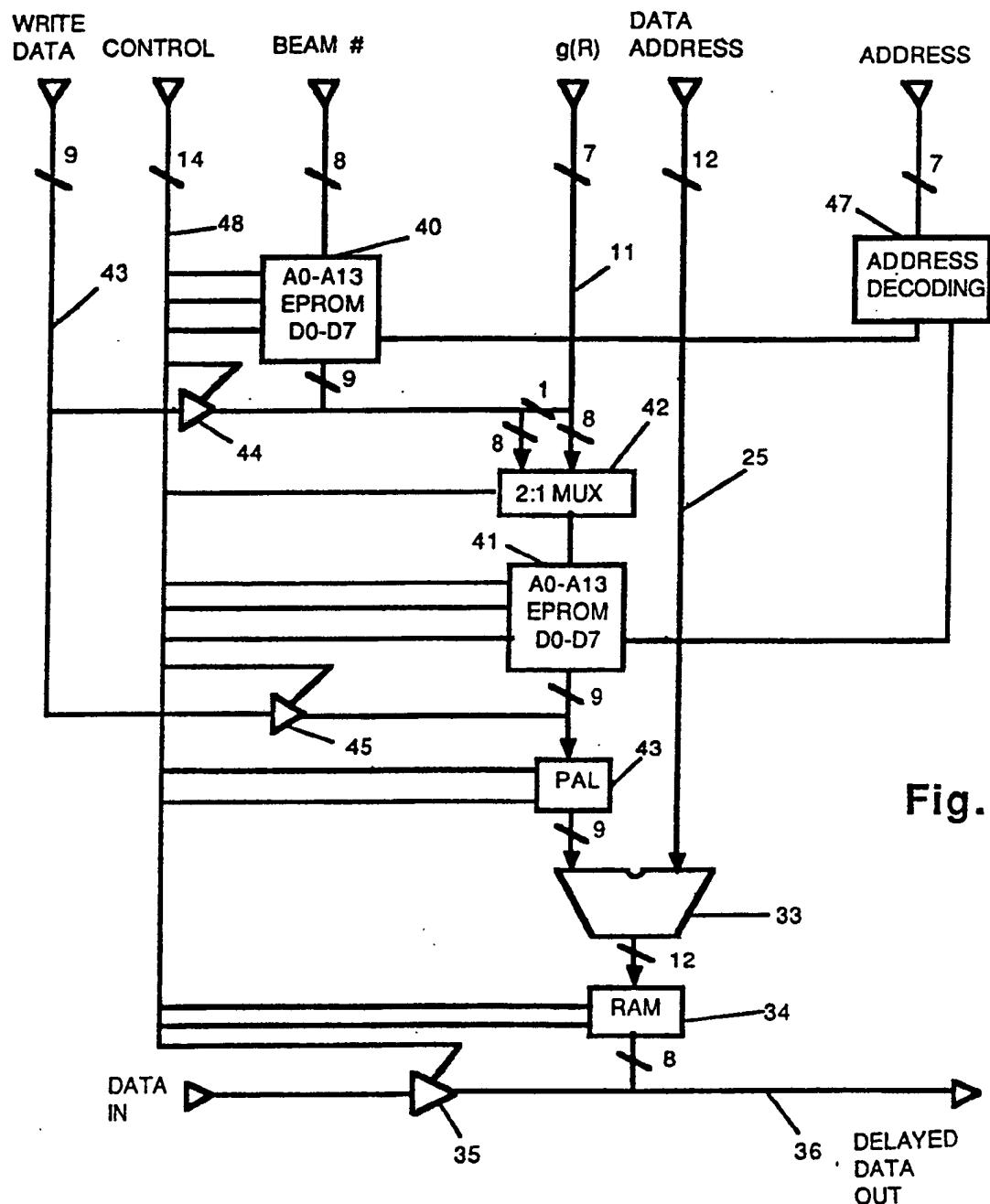


Fig. 6

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1.

DIGITAL DELAY GENERATOR FOR SONAR AND RADAR BEAM FORMERS

01
02 This invention relates to electronically
03 steered antennas such are used in sonar and radar
04 systems, and particularly to an antenna beamformer for
05 use in a multi-transducer array antenna.

06 A signal to be received from a specific
07 source has a spherical wave front which is received by
08 various transducers of a multi-transducer antenna at
09 different instants in time. In order to correlate the
10 signal wave front received by each transducer, the
11 signals received by each transducer must be
12 phase-shifted or time delayed. The delayed signals
13 are then summed to form an output signal. The amount
14 of time delay or phase shift introduced at each
15 transducer is a parameter which is directly related to
16 the radial distance from the specified source to the
17 particular transducer. The antenna can be steered to
18 any point in the object field by changing the delays
19 which are applied to the signals at each transducer.

20 The implementation of a practical beam
21 former using time delays of the signals received from
22 each of the transducers and summing the result has
23 proven to be a difficult problem. One of the major
24 difficulties has been the lack of a satisfactory means
25 for delaying the transducer signals individually by
26 precise and controllable amounts. There are two
27 aspects to this problem: the delay apparatus, and the
28 delay control apparatus. This invention relates to
29 the latter. The delay control apparatus is that part
30 of a beam former which determines and controls the
31 exact amount of delay which must be introduced at each
32 transducer in order to steer the beam to a specified
33 point in the object field.

34 A variety of electronic delay mechanisms
35 have been tried or proposed, including analog delay
36 lines, and charge coupled device analog shift
37 registers. More recently, digital storage circuits
38 such as semiconductor random access memories have been

01

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02 used as delay elements because of the large number of
03 samples they can hold and the very fine delay
04 resolution which can therefore be achieved.

05 Regardless of the delay mechanism employed, however,
06 the problem remains of determining the correct amount
07 of delay to introduce in each case. The required
08 delays are functions of the distances between each
09 transducer and each point in the object field. In the
10 general case of a three-dimensional transducer array
11 with arbitrary, but known, transducer locations, and a
12 three-dimensional object field, determination of the
13 delay values involves a large number of moderately
14 difficult computations.

15 This problem is usually minimised by
16 restricting the array geometry in such a manner that
17 symmetry and/or repetitiveness in the detector
18 locations introduces a high degree of redundancy into
19 the delay computations. The most obvious example of
20 restricted geometry is the linear array with equally
21 spaced elements. There are two significant
22 disadvantages to restricting array geometry: the
23 positions of the transducer elements must be a
24 compromise between beam former design requirements and
25 antenna performance considerations, and performance
26 will inevitably suffer as a result, and the resulting
27 beam former can only be used with arrays of the
28 specific geometry for which the beam former was
29 designed.

30 Another common method of increasing the
31 degree of redundancy in the delay computations is to
32 assume that all signals of interest originate
33 sufficiently far from the detector array that their
34 wave fronts are essentially planar across the aperture
35 of the array. The disadvantage of this approach is
36 that the antenna is incapable of focusing and is thus
37 restricted to far-field targets. Although not a
38 significant limitation for small aperture, low

02 performance sonars, this inability to focus on
03 near-field targets is unacceptable in large aperture,
04 high resolution applications.

05 The redundancies introduced by the
06 combination of restricted array geometry and the
07 far-field approximation can reduce the quantity and
08 complexity of delay computations considerably. For a
09 few very simple array geometries, such as the linear
10 array of equally spaced transducers, the computational
11 requirements are negligible.

12 Another approach to the problem of delay
13 value determination, which does not restrict array
14 geometry or aperture, employs the general purpose
15 digital computer. The detector signals are digitized
16 and loaded into computer memory where the beam forming
17 operation is performed entirely in software, usually
18 in the frequency domain using Fourier transform
19 techniques. Although offering unparalleled
20 flexibility, this approach is unacceptably slow for
21 many real time beam forming applications.

22 It is possible to pre-compute the delay
23 values for each transducer for all possible points in
24 the object field and store the results in look-up
25 tables, one for each transducer, where they can be
26 accessed very rapidly as required. This approach
27 combines the flexibility of the general purpose
28 computer with the speed of a dedicated hardware
29 beam former, but it has the disadvantage that a
30 three-dimensional object field with acceptable spatial
31 resolution requires excessively large look-up tables.
32 Thus for example to provide an acoustic imaging system
33 with an object field of 128 pixels by 128 lines and
34 the ability to focus at 64 different ranges, a look-up
35 table for each transducer in such a system would have
36 to contain 1,048,576 words. Clearly the memory
37 requirements for such digital systems are extremely
38 great.

02 An example of a beam former using
03 precomputed delay values stored in digital look-up
04 tables is described by Petersen and Kino in "Real-time
05 Digital Image Reconstruction: A Description of Imaging
06 Hardware and an Analysis of Quatization Errors", IEEE
07 Transactions on Sonics and Ultrasonics, Volume SV-31,
08 Number 4, July, 1984, pp. 337-351. In this beam
09 former the delay values are stored in a high-speed
10 look-up table called a "focus map".

11 In these and all other known examples of
12 beam former designs using pre-computed delay values
13 stored in digital look-up tables, the array geometry
14 is restricted in order to take advantage of symmetry
15 and repetitiveness. The redundancy thus introduced
16 into the delay computations reduces the size of the
17 look-up table to manageable proportions. No prior
18 example is known of a beam former using stored,
19 pre-computed delay values for a three-dimensional
20 transducer array of arbitrary geometry, to image a
21 high-resolution, three-dimensional object field.

22 The present invention is a beam former
23 apparatus which uses precomputed beam steering
24 information stored in digital look-up tables to
25 control the time delays introduced at each transducer
26 of three-dimensional transducer array with arbitrary
27 but known geometry to image a three-dimensional object
28 field with high spatial resolution, and high speed
29 (operating in real time), yet using substantially
30 reduced memory from that required in the aforenoted
31 prior art approach. For the case of an image field of
32 128 pixels by 128 lines, focusing at 64 different
33 ranges, rather than more than 1,000,000 digital delay
34 words previously required for each of the transducers,
35 the present invention requires only two memories, each
36 storing 16,384 words. This clearly represents a
37 substantial memory reduction over the prior art
38 system. In a system to be described below, it has

been found that depending on the duty cycle (the number of read cycles for every write cycle) beam output rates as high as 10,000,000 per second can easily be obtained.

In the present invention the look-up operation is partitioned in such a way that the excessively large look-up table previously required for each transducer can be replaced with two very much smaller look-up tables in a cascade configuration, thus providing a substantial net reduction in the total amount of look-up table memory required for each transducer.

The partitioning scheme utilizes the principle that the location of any point in three-dimensional object space can be fully defined by two direction coordinates and one range coordinate. Specifically, each target point can be defined by its distance (the target range) from a predetermined reference point, and by the direction (two coordinates) of the line from the reference point to the target. However, it can be shown that the beamsteering delay required at a particular transducer is a function only of the target range and the angle between the lines joining the predetermined reference point to the particular transducer and to the target, and is independent of the actual target direction. Thus the two direction coordinates of each object point can be replaced with a single parameter (for each transducer): the angle between the lines joining the predetermined reference point to the particular transducer and to the target. This angle, which is in general unique to each transducer and each target point, is sufficient to specify the required delay for any given value of target range.

Thus in the present invention, the first look-up table for each transducer transforms the two target direction coordinates into a digital

02 representation of the angle between the lines joining
03 the predetermined reference point to the particular
04 transducer and to the target, and the second look-up
05 table for each transducer transforms the digital value
06 produced by the first look-up table for the
07 transducer, together with the target range, into a
08 digital delay control signal.

09 The present invention is a beam former
10 control apparatus for a multi-transducer array antenna
11 comprising a delay circuit for generating a delay or
12 phase shift control signal for the signal received
13 from (or, reciprocally, transmitted to) each
14 transducer. Each delay circuit is comprised of a pair
15 of look-up tables, the first look-up table receiving
16 one or a pair of signals which specifies the direction
17 of the beam. The input signals are representative of
18 an address in the look-up table. The word which is
19 read from the address in the first look-up table is
20 output to the second look-up table. That signal, in
21 combination with a second input signal which is
22 representative of the range of the target, forms an
23 address to the second look-up table. A word stored at
24 the address of the second look-up table is output
25 therefrom, and represents a delay, i.e. constitutes a
26 delay control signal for the associated transducer for
27 delaying the received signal prior to being summed in
28 a summer with the separately delayed signals of the
29 other transducers. In the case of a transmitting
30 antenna, it controls the delay of the signal prior to
31 being applied to the corresponding transmitting
32 transducer. More generally, in accordance with one
33 embodiment of the invention, each delay circuit is
34 comprised of a first digital apparatus for receiving
35 one or a pair of signals representative of a target
36 direction relative to a predetermined reference point,
37 which provides in response thereto a first signal
38 representing a function of an included angle between

01 lines joining the reference point to the corresponding
02 transducer and the reference point to the target, and
03 second digital apparatus in circuit communication with
04 the first digital apparatus for receiving the first
05 signal and a second signal representative of the range
06 of the target relative to the reference point, and for
07 providing in response thereto an output signal
08 corresponding to the control signal.

09
10 In accordance with another embodiment of
11 the invention, a multi-transducer array antenna is
12 comprised of a plurality of digital time delay
13 apparatus, one corresponding to each transducer for
14 delaying transmission of a signal traversing
15 therethrough, and including a delay control input.
16 Analog-to-digital converter apparatus is connected to
17 each transducer for receiving an output signal
18 therefrom, having an output connected to an input of a
19 corresponding time delay apparatus. A summer has
20 inputs connected to corresponding outputs of the time
21 delay apparatus, for receiving variously delayed
22 output signals of the transducers and for providing a
23 beam output signal of the antenna. Control apparatus
24 controls the time delay of each time delay apparatus.
25 Each control apparatus is comprised of a first look-up
26 table for receiving a signal representative of the
27 direction of the line joining the target to a
28 predetermined reference point as an address, and for
29 outputting in response thereto a first signal, stored
30 at the address, representative of an included angle
31 between lines joining the corresponding transducer to
32 the reference point, and the reference point to the
33 target of the corresponding transducer. A second
34 look-up table receives the first signal and a second
35 signal representative of the range of the target
36 relative to the reference point as an address and
37 outputs in response thereto a delay control signal
38 stored at the address. The delay control signal is

02 applied to a corresponding delay control input of a
03 corresponding delay apparatus for controlling the
04 delay of transmission of the signal from the
05 corresponding transducer therethrough. Of course the
06 look-up table can be combined into a single memory if
07 the address requirements are dealt with in accordance
08 with the art.

09 The signals representative of the
10 direction and of the range of the target are provided
11 from an external source which does not form part of
12 this invention (e.g. from a manual control panel) and
13 can simply be digitally converted signals
14 corresponding to d.c. voltages established by a
15 potentiometer connected across a d.c. power source, or
16 equivalent apparatus. The transducers can be
17 typically hydrophones in a sonar system, array
18 elements of a radar antenna, etc.

19 A better understanding of the present
20 invention will be obtained by reference to the
21 detailed description below, in conjunction with the
22 following drawings, in which:

23 Figure 1 is a schematic drawing
24 illustrating the basic principles of a beam former,

25 Figure 2 is a block diagram illustrating
26 the basic concepts of the present invention,

27 Figure 3 is a block diagram of a beam
28 former which utilizes the present invention,

29 Figure 4 is a block schematic diagram of
30 one embodiment of the invention which can be used in
31 the configuration of Figure 3,

32 Figure 5 is a schematic of an embodiment
33 of the invention, and

34 Figure 6 is a schematic of another
35 embodiment of the invention.

36 Turning to Figure 1, the basic concept of
37 the multi-transducer antenna beam former is
38 illustrated. An antenna 1 is formed of representative

01
02 transducer 2A-2E which for purposes of illustration
03 are arranged in a single plane. A reference point 3
04 and a target 4 are for illustration purposes located
05 in the same plane as the transducers. The target 4 is
06 a source of signals to be received (in the receiving
07 case) which could be generating the signals or
08 reflecting or scattering signals generated elsewhere.
09 The speed of propagation in the medium is assumed to
10 be the same at all points and in all directions, so
11 the signals travel with spherical wavefronts from the
12 target, as illustrated by line 5.

13 Clearly each wave front is interrupted by
14 transducer 2E and 2D before being interrupted by
15 transducer 2C which is earlier than the time that the
16 same wave front is intercepted by transducers 2B and
17 2A. In order to correlate the signals from all
18 transducers, the signals from transducers closer to
19 the target must be delayed by amounts equal to the
20 additional travel time that it takes the same
21 wavefront to reach the transducer most distant from
22 the target. The travel time from the target to any
23 transducer is equal to the distance between the target
24 and the transducer divided by the propagation speed in
25 the medium. The required delays can therefore be
26 expressed in terms of the array and object field
27 geometry. With reference to Figure 1, the delay
28 required at transducer 2C is defined by the
29 expression:

30 $\text{delay} = (r_{\max} - r)/c$
31 where r_{\max} is a reference distance equal or greater
32 than the distance between the target and the
33 most distant transducer in the array,
34 r is the distance between the target and
35 transducer 2C, and
36 c is the propagation speed of the received
37 signal in the medium in which it travels,

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02 The simplicity of this expression is
03 deceptive, because in general r is not known
04 explicitly, but must be computed or otherwise
05 determined for each transducer from the known
06 transducer and target coordinates every time a new
07 target is selected. Furthermore, although the example
08 was illustrated in two-dimensions, object fields are
09 often three-dimensional, and may contain thousands of
10 resolvable target points. The time required to
11 perform these computations is particularly critical in
12 real-time tracking, scanning and video applications
13 which require the ability to change the steering
14 delays very rapidly and frequently.

15 As was mentioned earlier, one way of
16 achieving the above is to provide a transducer time
17 delay control for each transducer comprising a memory
18 which contains a look-up table for the time delay for
19 each elemental position in three-dimensional object
20 space for translation of the signal from each
21 transducer. Thus for an object field of 128 pixels by
22 128 lines, and at 64 different ranges, the look-up
23 table for each detector would have to contain
24 1,048,576 entries.

25 Instead, according to the present
26 invention, a delay control apparatus is used for each
27 detector as shown in Figure 2. In the present
28 invention a pair of look-up tables 7 and 8 are used.
29 An m bit address signal is applied to the m address
30 lines 9 of look-up table 7, which address signal is
31 representative of the beam direction for an associated
32 transducer. A resultant output signal on the n output
33 lines 10 of look-up table 7 is applied to n address
34 input lines of look-up table 8. At the same time a
35 range signal made up of $x-n$ bits is applied to $x-n$
36 address lines 11 which are input to look-up table 8.
37 The resulting y bit output signal (with fewer number
38 of bits than x) from look-up table 8 on y lines 12

01 represents the delay to be applied to the signal
02 received from the associated detector array before
03 summing with the signals from the other arrays (or
04 alternatively applied to the signal to be transmitted
05 from a corresponding transducer prior to being applied
06 to that transducer).

07 The input signal on input lines 9
08 represents beam direction. In the two-dimensional
09 example of Figure 1, this direction could be specified
10 by a single parameter, for example, the angle (from
11 the horizontal) of the line between the target 4 and
12 the reference point 3. In the general
13 three-dimensional case two coordinates, azimuth and
14 elevation for example, are required to unambiguously
15 specify the beam direction.

16 In one example, the azimuth input signal
17 to look-up table 7 could be formed of a 7 bit word.
18 The corresponding elevation input would be similarly
19 formed of a 7 bit word. Thus the address to look-up
20 table 7 would be 14 bits. Yet the output word from
21 look-up table 7 which is the function of the angle of
22 A could be specified with e.g. 8 bits, an overall
23 reduction of six bits or a factor of 64.

24 The output word is applied as part of an
25 address signal to look-up table 8. The remainder of
26 the address signal, representative of the range of the
27 target is applied on input lines 11. The word
28 representing the range would typically be 6 bits.
29 Consequently the address of look-up table 8 would be
30 14 bits.

31 The addressed delay control data stored in
32 look-up table 8, is output on lines 12, would be e.g.
33 8 bits, a substantial reduction from the input address
34 word length. This output signal constitutes the delay
35 control, with sufficient bit length to define the
36 required resolution.

01 - 12 -

02 The look-up tables used in this example
03 contain 2^{14} (16,384) words each, for a total of 32,768
04 words, a substantial reduction from the 1,048,576
05 entries in the prior art approach.

06 The geometric basis for the present
07 invention can be illustrated by rewriting the delay
08 expression developed above in slightly different
09 form. Referring again to Figure 1, the required
10 delays can conveniently be specified relative to the
11 time of arrival of the wave front at a real or
12 hypothetical transducer located at the reference point
13 3. Recalling that the distance from the reference
14 point 3 to the target 4 is defined as the target
15 range, the amount of delay which must be applied to
16 the signals from transducer 2C is equal to:

17 $\text{delay} = d_{\text{ref}} + (R-r)/c$

18 where d_{ref} is the delay required at reference
19 point 3, and

20 R is the target range.

21 The plane triangle formed by the target, the reference
22 point and transducer 2C can be solved for r to permit
23 the delay expression to be written as:

24 $\text{delay} = d_{\text{ref}} + [R - (R^2 + x^2 - 2Rx \cos A)^{1/2}]/c$

25 where A is the angle between the lines joining the
26 reference point to the target point and to
27 transducer 2C, and
28 x is the distance between the transducer and
29 the reference point.

30 Note that although illustrated in two-dimensions, this
31 expression is fully valid in three-dimensional space.

32 The significance of this form of the delay
33 expression is that, for any given transducer, the
34 beamsteering delay is a function of only two variable
35 parameters, R and A. Furthermore, the angle A is
36 uniquely specified for any given transducer by the
37 beam direction (the direction of the line from the
38 reference point to the target point), and by the

01 transducer location, and is independent of target
02 range R. Thus, the two beam direction coordinates
03 (e.g. pixel and line, or azimuth and elevation) can be
04 transformed into a single intermediate parameter (A),
05 quite independently of the range coordinate (R),
06 thereby reducing the three-dimensional look-up
07 operation to two, cascaded two-dimensional look-up
08 operations. The delay signal has thus been
09 transformed from a three-dimensional problem to a
10 two-dimensional problem, requiring substantially
11 reduced memory relative to a three-dimensional
12 parameter storage memory.

13 Look-up tables 7 and 8 can be random
14 access memories. A single chip 128k memory used for
15 look-up table 7, for example type 27128, can
16 accommodate a total of 16,384 distinct beam direction
17 words. This is sufficient for an image field of 128
18 pixels by 128 pixels or 360 increments in azimuth by
19 45 in elevation. In the worst case (full spherical
20 coverage) this size memory is capable of providing two
21 degree resolution in both azimuth and elevation,
22 although defining the beams in this manner may not be
23 the most efficient use of look-up table addresses, if
24 the criterion is uniform angular coverage of the
25 object field. It should be noted that the address
26 code can be regarded simply as a listing of the beam
27 directions, in any convenient order (for example, a
28 raster scan sequence), and the beams can be randomly
29 accessed.

30 The address field of the 27128 memory chip
31 is 14 bits wide. A similar memory chip can also be
32 used for look-up table 8. Since 8 bits of the input
33 address to look-up table 8 are used to specify the
34 function of the angle A (the output from look-up table
35 7) 6 bits are available for range data (x-n). The
36 most efficient coding scheme is one which produces a
37 uniform distribution of delay errors from infinity to

02 the minimum distance at which the beam former can
03 focus.

04 The effect of range resolution on the
05 delay determination is highly non-linear, ranging from
06 very large in the near field to insignificant in the
07 far field. An unencoded range input would require a
08 wastefully large look-up table address word length to
09 provide acceptable resolution for near field target.
10 For that reason it is desirable to increase the number
11 of words stored for the near field ranges and decrease
12 the number of ranges for the far field, i.e., inverse
13 to the non-linearity.

14 Thus each time delay control circuit is
15 identical, except for the data stored at each memory
16 location of the look-up tables.

17 Figure 3 is a block diagram of a digital
18 time delay and sum beam former. Transducers 15
19 intercept the signals to be received from the target.
20 The received signals pass through associated
21 amplifiers 16 and the amplified signals are
22 respectively applied to analog-to-digital converters
23 17. Here the signals are converted to digital form,
24 and are then applied to controllable time delay
25 circuits 18. After being time delayed, the digitized
26 signals from the transducers are applied to inputs of
27 a summer 19, the output thereof being the beam output
28 signal of the antenna, on transmission path 20. A
29 timing and control circuit 21 controls the time delay
30 in delay circuits 18, as well as the operation of
31 analog-to-digital converter 17 and summer 19. The
32 timing and control circuit 21 applies control signals
33 to time delay circuits 18 to achieve electrical
34 steering (beamforming) of the antenna to fulfill the
35 delay characteristics required to identify the unique
36 position in three dimensional space defined by the
37 position of target 4 as described above with respect
38 to Figure 1, within the resolution capability of the

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02 antenna.

03 Figure 4 illustrates the time delay
04 circuitry, contained within each block of delay
05 circuit 18 in Figure 3. Look-up table 7, receives a
06 beam direction signal on input address lines 9. The
07 address can be specified merely as a predefined beam
08 number, which has been pre-standardized to represent a
09 certain direction.

10 The output signal of look-up table 7 is
11 applied via output lines 10, with a range address
12 signal from input lines 11, to the address inputs of
13 look-up table 8. The range input signal could
14 alternatively be represented as a range code which has
15 been predefined to represent a predetermined range.
16 The range code and output signal of look-up table 7
17 together form an address input to look-up table 8,
18 which in response outputs a delay control signal on
19 output line 12.

20 The digitized signal received from the
21 target via a transducer 15 is applied via input data
22 line 23 to the data port DIN of a data memory 24. The
23 write address to be added to the output data signal
24 word from look-up table 8 is received on data address
25 lines 25, which lines are connected to an input of a
26 summer 26. The output signal of summer 26 is applied
27 to the address input of data memory 24.

28 Preferably the data address source signals
29 are generated in a counter which merely increments the
30 address location for writing the input data from the
31 transducer carried on data lines 23. Indeed, it is
32 preferred that data memory 24 should be a rotating
33 buffer which merely writes the data sequentially from
34 one end of the memory to the other, starting again at
35 the beginning, over-writing the old data once the end
36 of the memory has been reached.

37 The delay signal from look-up table 8 is
38 passed through AND gate 27, to the other input of

02 summer 26. The second input of AND gate 27 is
03 connected to a control input 28, which is also
04 connected to the read-write R/W input of data memory
05 24. The delayed input data is obtained at the data
06 output line 29 from data memory 24. The delayed data
07 output line 29 of each data memory is connected to a
08 corresponding one of the inputs of summer 19 (Figure
09 3).

10 In operation, external controller
11 circuitry (not forming part of this invention)
12 implements a write cycle. A write pulse is received
13 at control line 28, connected to the R/W terminal of
14 the data memory, and sets the data memory 24 to its
15 write mode. At the same time AND gate 27 is
16 inhibited. The data being received on input lines 23
17 from an associated transducer is written to the data
18 memory 24 at the address specified by the signals on
19 data address source lines 25.

20 Assuming that data memory 24 has been
21 filled with data from previous cycles, the data
22 address increments, and the control input 28 switches
23 to a read cycle. AND gate 27 is enabled, allowing the
24 output data from look-up table 8 to pass through into
25 summer 26. The address of the data on line 25 is thus
26 incremented by the value of the output data from
27 look-up table 8. The read address of data memory 24
28 is thus an increment from that address which has just
29 been written to, the increment representing a delay.

30 In this manner read and write cycles are
31 time multiplexed; it is preferable that there should
32 be several read cycles typically taking place for each
33 write cycle. The beam output rate is thus made
34 entirely independent of sample data input rate. The
35 sample rate is determined by beam forming time-delay
36 resolution requirements, rather than by sampling
37 theory, and is normally much higher than the Nyquist
38 rate.

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02 The time delay of a particular output
03 sample is simply the difference between the read
04 address and the write address multiplied by the
05 sampling interval. It should be noted that it is the
06 relative delay between the signals of the transducers,
07 rather than the absolute amount of delay, that is
08 important to beam forming.

09 The minimum capacity of the data memory,
10 in terms of the number of samples it will hold, is
11 determined by the sampling rate and the maximum delay
12 required, which is a function of the ray geometry and
13 steering angles. In practice a much larger data
14 memory should be used so that several samples of each
15 beam (in time sequence snap-shots) can be obtained
16 without having to wait for new data.

17 The word size of the data memory can be as
18 small as one bit, and in which case simple hard
19 limiting circuits can be used instead of the
20 analog-to-digital converters, or can be as large as
21 desired. The choice of word size would normally
22 depend on sonar or radar performance considerations
23 rather than on beam former technology limitations.

24 It should also be noted that the beam
25 number (direction) range code (range), the data
26 address and the various control signals are generated
27 externally and are common to all delay circuits in the
28 system. The only difference between circuits
29 associated with each transducer is the data stored in
30 the look-up tables.

31 The adder 26 performs the functions of
32 offsetting the delay relative to the current write
33 address so that none of the delay values overlap the
34 boundary between the old and the new data, and permits
35 the controller to step through a time sequence of
36 "snap-shots" of each beam.

37 Turning to Figure 5, an actual circuit
38 implementation of the block diagram of Figure 4 is

02 shown. The eraseable programmable read-only-memories
03 (EPROM) 30 and 31, each preferably type 27128 (128k)
04 are used as look-up tables 7 and 8. The 14 address
05 input ports A₀-A₁₃ receive the beam number word or
06 pair of words. The 8 data output ports D₀-D₇ of EPROM
07 30 are connected to 8 address lines of EPROM 31, while
08 6 input lines which carry the range code are connected
09 to the remaining address ports of EPROM 31, thus
10 supplying a 14 bit address signal to ports A₀-A₁₃.

11 The 8 data output ports D₀-D₇ of EPROM 31
12 (look-up table 8) are connected to the input of a type
13 273 latch 32. The output of latch 32 is connected to
14 an input of a type 283 summer 33. Latch 32 performs
15 the function of AND gate 27 (Fig. 4), and improves
16 system speed by removing the look-up table access time
17 from the data memory timing cycle. This is a benefit
18 because the data memory would normally be accessed
19 many times more frequently than the look-up table.

20 The data address signal (e.g. 11 bit) is
21 applied to the other input port of summer 33 via lines
22 25, and the 11 bit output port of summer 33 is
23 connected to the address ports A₀-A₁₀ of data memory
24 34. Data memory 34 can be a 2k x 8 static random
25 access memory (RAM).

26 The digitized input data from the
27 transducer is passed through tri-state buffer 35, and is
28 applied to the data ports D₀-D₇ of data memory 34.
29 The same port is used to read the delayed output data
30 to output line 36.

31 The memories 30 and 31 could of course be
32 larger, e.g. 512k to increase resolution, and as
33 memory cost reduces, this would be desirable. Each
34 memory as described is organized as 16,382 8 bit
35 words, and thus memory 30 can accommodate a total of
36 16,384 distinct beam directions, which as noted
37 earlier is sufficient for an image field of 128 pixels
38 by 128 pixels, or 360 increments in azimuth by 45 in

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02 elevation. Memory 31 produces an 8 bit delay value.

03 The remaining control lines for each of
04 the memories (e.g. \overline{CS} , \overline{WE} , etc.) are well known by
05 persons skilled in the art and need not be described
06 in detail.

07 Turning to Figure 6, another embodiment of
08 the present invention is shown. In this embodiment,
09 the look-up tables are implemented using dynamic
10 random access memories (DRAMs) 40 and 41. Each memory
11 has the capacity of 64k words by 9 bits per word.
12 DRAM 40 is addressed similarly to memory 30 in the
13 embodiment of Figure 5. However its data output lines
14 D₀-D₈ are connected to one group of inputs of a 2:1
15 multiplexer 42 with the range code data, lines 11
16 being connected to the other group of inputs. The
17 output port of multiplexer 42 is connected to the
18 address inputs A₀-A₇ of DRAM 41. The data output
19 lines D₀-D₈ of DRAM 41 are connected to the inputs of
20 latch 43, and the outputs of latch 43 are connected to
21 one set of inputs of adder 33. The other set of
22 inputs of adder 33 is connected to the data address
23 source lines 25, similar to the embodiment of Figure
24 5. The output of adder 33 is connected to the address
25 inputs of random access memory 34 which, in this case,
26 is a 4k word x 8 bit RAM.
27

28 The above-described circuit operates
29 similarly as the circuit of Figure 5, except for the
30 use of a multiplexer 42 for combining the output 9 bit
31 signal of DRAM 40 and the 7 bit range signal together
32 to form an 8 bit address word for DRAM 25. However
33 the data stored in dynamic random access memories is
34 volatile; the look-up table data must be downloaded
35 from the system controller whenever the system is
36 powered up. Being able to reload the look-up tables
37 is very advantageous in applications in which the
38 range geometry is slowly changing, such as when the

02 transducers are air-deployed drifting sonobuoys, e.g.
03 used in military submarine locating systems. The use
04 of 1-bit wide memories also permit greater flexibility
05 in look-up table input and output word lengths, but at
06 the expense of greater circuit complexity.

07 In order to load the memories, data to be
08 written in them is provided on data lines 43 from the
09 external controller. The data lines are connected to
10 the data ports of memory 40 via tri-state buffers 44,
11 and are connected to the data ports D₀-D₈ of memory 41
12 via tri-state buffers 45. External control lines are
13 connected to the control inputs of tri-state buffers
14 44 and 45 via bus 48.

15 Write address lines 46 carry memory
16 selection signals for DRAMs 40 and 41 from an external
17 controller to an address decoder 47 in which they are
18 decoded. Output lines of decoder 47 are connected to
19 the chip select inputs of random access memories 40
20 and 41.

21 To load the random access memories 40 and
22 41, the data is presented on the write data lines 43,
23 and is passed through either one of tri-state buffer
24 44 or 45 under control of a buffer enable signal
25 carried by the control bus 48. The memory selection
26 address appears on address bus 46, which is decoded,
27 and a resultant enable signal appears on the chip
28 select input of memory 40. The data is loaded into
29 the address defined by an address signal appearing on
30 the input address lines 9.

31 The data to be loaded on the memory 41 is
32 passed through the tri-state buffer 45 from the write
33 data lines 43, memory 41 being enabled by a signal
34 appearing on the address bus 46, which is decoded in
35 address decoder 47, and applied to the chip select
36 terminal of memory 41.

37 The look-up table data to be loaded
38 appears at the data terminals D₀-D₈ of memory 41 via

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02 buffer 45 and is loaded into the memory at addresses
03 specified by address data which passes through
04 tri-state buffer 44 under control of a signal on
05 control bus 48 and address data applied to address
06 lines 11. The address data passes through multiplexer
07 42 to the address inputs A₀-A₇ of memory 41. The
08 address data passing through buffer 44 is of course
09 not loaded into memory 40, since memory 40 at this
10 time is inhibited by an inhibit signal appearing at
11 its chip select input, as a result of the signal
12 decoded from address bus 46 in decoder 47.

13 During normal non-loading operation of the
14 circuit tri-state buffers 44 and 45 are placed in
15 their non-conductive states by control signals on
16 control bus 48. Both memories 40 and 41 are selected
17 by means of an address signal appearing on an address
18 bus 46, and decoded in decoder 47 to form the required
19 chip select signals.

20 The beam direction selection signal is
21 externally applied to address bus 9. The 9 bit word
22 stored at the addressed location in memory 40 is
23 output at the data outputs D₀-D₈ of the memory, and
24 appears at one of the input ports of multiplexer 42.
25 At the same time, the 7 bit range signal is externally
26 applied to lines 11, completing the address for memory
27 41. Multiplexer 42 combines the two signals and
28 applies an 8 bit address signal to the address ports
29 of random access memory 41 which in turn outputs a 9
30 bit delay signal stored at the address to latch 43.
31 The 9 bit latched signal is applied to one of the
32 ports of adder 33 which combines with the 12 bit data
33 address signal on bus 25, and provides an address
34 signal to random access transducer data memory 34.

35 An external controller can be designed by
36 a person skilled in the art of controller design to
37 provide the external signal requirements as described
38 above. The remainder of the circuit operates

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02 similarly to that described above with respect to
03 Figure 5.

04 The delayed transducer data output signal
05 carried by lines 36 from each of the circuits
06 described is applied to digital summer 19 (Figure 3)
07 where it is added to provide the output signal of the
08 antenna on transmission path 20.

09 The beam former described herein is
10 inherently suited for expansion. This is accomplished
11 very effectively by designing the basic beam former
12 unit to accommodate a fixed number of transducer
13 channels (64 for example), and expanding by operating
14 two or more units in parallel.

15 Additional beam formers operating on the
16 same transducer data in parallel can be used to
17 increase the number of beam samples per second (of the
18 same number of beams), or to increase the number of
19 beams at the same beam output rate, or both. In
20 either case a logical place to connect additional
21 beam formers is following the analog-to-digital
22 converters, to avoid functional duplication.

23 Similarly, two or more beam formers can be
24 paralleled to handle a large number of transducers,
25 although in this case the digital summer would have to
26 be expanded.

27 The basic delay circuits described above
28 are applicable to transmitting as well as receiving.
29 In a transmitting application the transducer data
30 memory (24 or 34) would be programmed with a suitable
31 waveform (e.g. a chirp) and a digital-to-analog
32 converter followed by a power amplifier would be
33 connected to its output to drive an associated
34 transducer element.

35 The beam former described above is
36 applicable to either active or passive roles. When
37 employed as a receive beam former in a sonar
38 application, the range code generated by the system

02 controller preferably is increased linearly with time
03 following each transmit pulse so that the received
04 echoes would always be in focus. In passive receiver
05 applications the range function can be under operator
06 control.

07 The design is also applicable to
08 phase-shift beam formers. In fact, since fewer bits
09 would normally be required to specify a phase shift
10 than a time delay, the output word length of the
11 second look-up table (reference 8 in Figure 4) could
12 be reduced.

13 While the system embodiment described
14 herein is directed to an acoustic sonar application,
15 the system can also be used in radar systems as well,
16 particularly phased array radar systems with a
17 digitally controlled phase shifter. Low frequency
18 radars such as those used for over-the-horizon
19 applications could use the beam former directly in
20 baseband.

21 The beam former described herein is also
22 fully compatible with systems employing correlation
23 processing of the beam signal output for pulse
24 compression or for detection of coded pulses.

25 A person understanding this invention may
26 now conceive of variations in design or other
27 embodiments, using the principles described herein.
28 All are considered to be within the sphere and scope
29 of this invention as defined in the claims appended
30 hereto.

CLAIMS

1. Beam former control apparatus for multi-transducer array antenna comprising:

a delay circuit for generating a delay or phase shift control signal for each transducer, each delay circuit comprising a first digital apparatus for receiving one or a pair of signals representative of a target direction relative to a predetermined reference point and for providing in response thereto a first signal representing a function of an included angle between lines joining the reference point to the corresponding transducer and the same reference point to the target, and a second digital apparatus in circuit communication with the first digital apparatus for receiving the first signal and a second signal representative of the range of the target relative to the reference point and for providing in response thereto an output signal corresponding to said control signal.

2. Apparatus as defined in claim 1 in which each of said digital apparatus is comprised of a first look-up table for receiving said representative target direction signals as a first look-up table address and in response for reading a corresponding digital word defining said first signal, and a second look-up table for receiving said first signal and said second signal as a second look-up table address and in response for reading a corresponding digital word defining said output signal.

3. Apparatus as defined in claim 1 or 2 in which the second look-up table contains more words

defining the near field delay values than far field delay values, whereby antenna resolution of the near field is rendered higher than that of the far field.

4. Apparatus as defined in claim 1 or 2 in which the look-up tables are comprised of random access memory means.

5. A multi-transducer array antenna comprising:

(a) a plurality of digital time delay means, one corresponding to each transducer, for delaying transmission of a signal therethrough, and including a delay control input,

(b) analog to digital converter connected to each transducer for receiving an output signal therefrom, having an output connected to an input of a corresponding time delay means,

(c) summing means having inputs connected to the outputs of the time delay means, for receiving output signals of the transducers and for providing a beam output signal of the antenna, and

(d) control apparatus for controlling the time delay of each time delay means, each control apparatus comprising a first look-up table for receiving a signal representative of the direction of a target relative to a predetermined reference point and for outputting in response thereto a first signal representative of an included angle between lines joining the reference point to a corresponding transducer and the same reference point to the target, and a second look-up table for receiving the first signal and a second signal representative of the range of the target relative to the reference point and for outputting in response thereto a delay control signal,

(e) means for applying the delay control signal to a corresponding delay control input of a

corresponding delay means for controlling the delay of transmission of a signal from a corresponding transducer therethrough.

6. An antenna as defined in claim 5 in which the look-up tables for each time delay means are comprised of random access digital memories storing words representative of said first signal and said delay control signals at predetermined address locations, said target direction signals being in the form of a beam direction specification constituting a first digital address for reading a word located at a corresponding address location, said second signal being in the form of a range code specification constituting a second digital address in combination with said first signal for reading a word located at a corresponding address location corresponding to said delay control signal.

7. An antenna as defined in claim 6 in which each time delay means is comprised of a digitally controlled phase-shifter.

8. An antenna as defined in claim 6 in which each time delay means is comprised of a data memory for writing digital signals output from a corresponding analog to digital converter, and for reading the data memory at an address specified by a corresponding delay control signal.

9. An antenna as defined in claim 8 in which the data memory is in the form of a rotating buffer, including means for writing said digital signals at sequential address locations, and means for reading said digital signals therefrom at sequential address locations spaced from writing addresses by an address increment defined by the delay control signal.

10. An antenna as defined in claim 9 including a latch connected to the data output of the second look-up table for temporarily storing the delay control signal for addressing the data memory.

11. A method of controlling the beam direction of a multi-transducer antenna comprising storing first digital words representative of included angles between lines joining a reference point to a transducer and the same reference point to the target, for each transducer in a corresponding look-up table, storing second digital words representing delay control signals corresponding to ranges of a target relative to the reference point for each of said first digital words in a second look-up table associated with the first look-up table for each transducer, addressing each first look-up table with an address signal representing the direction of said target to obtain a corresponding first digital word, addressing each second look-up table with a corresponding first digital word combined with a signal representing the range of the target to obtain a corresponding second digital word, and delaying a signal received by a corresponding transducer an amount represented by the second digital word.

12. A method as defined in claim 11 in which the number of bits in the first digital word is smaller than the number of bits in the address signal representing the direction of the target.

13. A method as defined in claim 11 or 12 including storing the signal received by each transducer at sequentially stored locations, and repeatedly reading the stored signal at locations offset from the storing locations by an amount represented by the second digital word.

14. Apparatus according to claim 1 substantially as herein described with reference to and as shown in any of Figures 2 to 6 of the accompanying drawings.

15. An antenna according to claim 5 substantially as herein described with reference to and as shown in any of Figures 2 to 6 of the accompanying drawings.

16. A method according to claim 11 substantially as herein described with reference to and as shown in any of Figures 2 to 6 of the accompanying drawings.